New Command and Control Methods for Proximal Interaction between Soldiers and Robots

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Abstract

This paper addresses soldier assessments of new methods of interaction with robots. Assessments were needed to support new capabilities requested in a Joint Urgent Operational Needs Statement (JUONS) for the US Army Rapid Equipping Force (REF) to lighten the load for soldiers in Afghanistan. Two real-world user assessments indicate potential for a new form of command and control based not on maps or global positioning system (GPS) but based on proximal interaction using lead and follow behaviors. The assessments include a variety of subjective and objective data indicating the benefit of the approach for dismounted route clearance operations on long patrols. Results indicate value to having robots follow and lead dismounted troops as well as the ability to wagon train multiple robots. The research indicates that it is possible to meet the requirement that robots require less than 5% of the soldier's workload and can keep up with the patrol for an entire day. From a command and control perspective the novel aspect of the technology is that the workload requirement was met without dependence on the traditional command and control approaches of GPS based navigation or tele-operation. Other key performance metrics include maintaining an average operational tempo of over 2 mph for 15 miles of varied terrain including wooded trails, open fields and urban environments.

Introduction

The burden of weight carried by our soldiers in backpacks in Afghanistan and previously Iraq is extreme. In response to a Joint Urgent Operational Needs Statement (JUONS), the Army's Rapid Equipping Force (REF) is seeking new robotic and robot control capabilities to lighten the soldier load, both in terms of physical and mental workload. 5D Robotics, Inc. is helping to address these urgent military needs and through real-world robotic experiments and interviews with soldiers. This includes investigating new metaphors for human-robot interaction. The work has focused on supporting dismounted soldiers working in a proximal setting with small, medium and large robots ranging in size from 5lbs to 5000lbs. This paper describes assessments of two robot systems: the Mesa Armored Combat Engineer Robot (ACER) that weighs in over 5000lbs. and the Segway Robotic Mobility Platform (RMP) 400 series that weighs about 250lbs. Both of these robots can carry packs and supplies and detect buried hazards. For dismounted soldiers on the move, the option of continuous tele-operation is not a possibility since workload must be used for a variety of other critical tasks. On the other hand, fully autonomous approaches that rely on global positioning systems (GPS) have failed to operate reliably.

This paper considers the challenges and opportunities to reliably coordinating humans and mobile robots in close proximity using a combination of lead and follow behaviors to autonomously drive the robot in front of and behind the human at a minimal but safe distance. The capability is being applied to multiple applications but for the purposes of this investigation the focus is on supporting dismounted (foot) patrols, with special emphasis on route clearance whereby soldiers must travel a predetermined route from point

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14. ABSTRACT
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A to point B in a single day while detecting, marking and neutralizing hazards along the way. Traditional command and control approaches utilize a map-based metaphor which assumes accurate global positioning, up to date terrain data and continuous, high bandwidth data communication between the vehicles and humans in the patrol. The command and control challenge is that none of these are good assumptions. GPS is often unavailable or inaccurate due to jamming or canopy cover. Terrain data are often incomplete or no longer up to date. Data connectivity is a luxury rather than a rule especially given the communication jamming technology often used to prevent the detonation of Improvised Explosive Devices (IEDs).

Consequently, a new control approach has been developed which emphasizes proximal interaction, and the ability to respond in real-time to nearest neighbor motion. The new control approach abandons the use of GPS and long range radio frequency (RF) communication entirely in favor of reactive behaviors for lead, follow, and obstacle avoidance. An X-Box controller is used to lock the robot laser onto a human target who can then initiate either the lead or follow behavior. The vehicle responds directly to the human's speed and direction and can reason about the human's location even when they disappear behind a tree or around a corner. The vehicle also takes initiative to get around obstacles including other humans who may obstruct the path to the target. The main focus of the experiments was showing that the proximal interaction scheme involving follow, lead and wagon training provides significant benefit in terms of reducing workload, increasing operational tempo and reducing vulnerability to lost GPS.

Background

A key requirement of collaboration is relative spatial awareness of each robot and human team member. Traditional approaches rely on the GPS however; GPS is not always accurate and available to support precision detection, marking, and neutralization[i]. To avoid dependence on explicit communication and positioning, behavior-based approaches in the past have emphasized the need to have multiple, prioritized reactive behaviors that vie for control of the robotic mission.[ii],[iii]. Other work has focused on the role of the human to coordinate multiple vehicles and tasks and the software that can facilitate situation awareness and system understanding[iv],[v] . However, a purely reactive approach cannot benefit from the ability to plan based on time or position. To compensate for this lack it is possible to augment the reactive control approach with input from the human which can help to coordinate multiple vehicles and tasks[vi],[vii]. However, this requires reliable communication between the human and the robot and places a burden on the human to support the operation. During dismounted tasks, the human does not have the ability to devote large amounts of workload to the control of the robot. Moreover, the reactive approach in this case, depends on the ability to sense the human and both visual, thermal and laser based tracking schemes are often stymied by dust, rain, fog and vegetation.

To address these challenges, 5D has developed a highly accurate positioning system based on ultra wideband (UWB) active RF position tags. This system provides a means to coordinate effective collaboration between humans and multiple unmanned ground vehicles (UGV) and aerial systems (UAS) assets as they move through varied terrain to do a variety of missions. This invention provides an innovative means of spatial understanding and relative positioning to overcome limitations of GPS. The UWB tags and transmitters provide the ability to coordinate activities and cue individual behaviors using the active tags as a means of distributed activation. This is a concept drawn from the insect world where pheromones can be used to instigate, coordinate and limit swarm behavior of ants and other insects. In

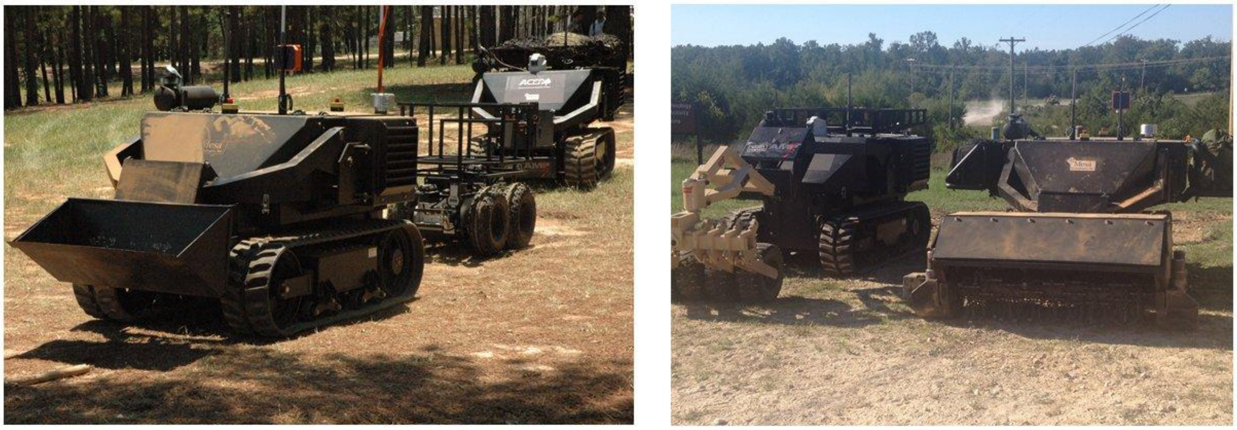

Figure 1: The ACER and Segway robots as part of a wagon train in a route clearance mission (left). The image at right shows the ACER with different configurations for route clearance (mine roller on left and mine flail on right).

much the same way, UWB tags can serve as pheromones to activate individual behaviors on robots, air vehicles and even on humans who can choose to respond to active position tags as they view their personal digital assistant (PDA) or smart phone. The tags themselves consist of a small radio transceiver, power, and antenna(s) and can be affixed to robots or clipped to a belt or backpack on a soldier.

The 5D UWB positioning technology uses a Social Potential Field concept to enable distributed swarm behaviors. In this method, each tag emits a signal which is treated like an attraction or repulsion force field. Attraction causes autonomous entities to come towards them whereas repulsion causes autonomous entities to move away. By changing the distance parameter in the Active Position Tag software, it is possible to increase the force field and accelerate the attractive or repulsive effect. Also, by varying the ID inherent in each tag signal it is possible to selectively coordinate activities of certain autonomous entities but not others. This selectivity is important for more complex group interactions. An important aspect of the invention is that the distance and heading information from the tag enables attraction and repulsion when coupled with autonomous behaviors for follow and avoidance. The tag capability must be coupled to the software behaviors on the individual vehicle entities to enable the follow, lead, convoy and avoidance behavior.

By employing a reactive, nearest neighbor approach, the lead, follow and avoidance behaviors provide a means for distributed intelligence and coordination. Collaborative behaviors enable the human to task multiple UGVs to: a) move through terrain collaboratively (e.g., lead me, follow me, and maintain minimum and maximum separation buffers), b) collaboratively search areas for hazards (e.g. the smaller vehicle can enter areas inaccessible to the larger) c) provide confirmation of hazards detected by the other robot and d) neutralize hazards that have been marked by the other.

The Route Clearance mission requires moving long distances while detecting, confirming, marking, and neutralizing a spectrum of IEDs in remote rugged terrain. Of particular significance is the dismounted route clearance mission which requires soldiers to be on foot since the larger combat and transport vehicles are too large to go on the double track and single track trails. No individual UGV can accommodate all terrain, hazard types, and mission constraints to address these threats[viii]. Larger UGVs can carry greater loads and quickly search terrain whereas smaller UGVs can access narrow passages and search areas blocked by debris and/or structures (e.g., guardrails). Both large and smaller robots are

needed (see Figure 1). The large vehicle should have the ability to travel at speeds over 5 mph and carry equipment (e.g., detectors, flail, small UGV) for distances over 20 miles. The small UGV should be man-transportable and should be able to traverse narrow passages between buildings and under road-side guard rails. Both types of robots are used in the three assessments described following.

System Design

The paper describes results from two military assessments at Ft. Leonard Wood, MO and a third assessment at Exponent Inc. facilities near Phoenix, AZ. These efforts were all focused on supporting soldiers while they accomplish long-range dismounted missions on single and double track paths. The first study used the 5000lb ACER robot to detonate buried explosives while moving ahead of the squad in a lead formation. The second used a 250lb Segway RMP-440 robot that autonomously followed behind the squad carrying 200lbs of critical equipment (including packs, water and food) in what is called a "lighten the load" follow formation. The third used a Segway RMP-440 with a different configuration as designed and built under contract with Exponent, Inc. All vehicles were equipped with the 5D Behavior Engine™ software and a light detection and ranging (LiDAR) that enable the vehicles to perform

Figure 2. Two ACER robots work together in a route clearance task.

autonomous leader and follow behaviors while also doing guarded motion (e.g., stop before collision) and obstacle avoidance (e.g., navigate around and past obstacles). The focus of these studies was to understand the concept of operation for inserting autonomous vehicles into a squad as a trusted peer and to measure the ability of the system and software behaviors to lower cognitive and physical workload. Figure 2, shows two ACERs being used together at Ft. Benning, GA (not part of this study) in a follow formation where the first vehicle uses a flail to detonate IEDs and landmines while the second follows autonomously carrying gear in the rack on top. The route clearance assessment performed at Ft. Leonard Wood, MO included use of a flail and a roller for detonating IEDs and landmines while moving along double-track dirt roads. The Microsoft X-Box controller was used to cue behaviors for lead, follow, neutralization and occasional tele-operation. The ACER is a 5000lb armored tank that can survive small

arms fire and explosions of anti-personnel mines. The versatile ACER uses a hydraulic drive to actuate a variety of attachments.

The Segway RMP-440X, shown in Figure 3 at left, is a militarized version of the Segway personnel transport (PT) that can carry 300lb. Unloaded it can travel at speeds up to 18mph. It can follow soldiers on narrow, unimproved paths and can climb 30 degree slopes to keep up with soldiers on rugged terrain. Also shown in Figure 3, at right, is the Exponent Segway used for Assessment 3.

Figure 3. Segway 440X shown here at left with the Adaptive Mission Payload (AMP), a generator and 200lbs of supplies. At right is the Exponent configured Segway with UWB tags in the black cases just above and forward of the tires.

Assessment One

Test Execution

Two ACERs were used together in a variety of route clearance exercises where the soldiers were permitted to try out various configurations and formations of soldiers and vehicles in order to accomplish the mission. The assessment took place over the course of a week at Ft. Leonard Wood, MO at the Maneuver Support Center (MANSCEN) Battle Laboratory. The hand-held controller was the Microsoft X-Box and the robotic behaviors were orchestrated by the 5D Behavior Engine. The assessment also included detailed interviews with 32 combat engineers who had been trained to accomplish mine detection and Improvised Explosive Device Defeat (IEDD) operations. Over half of these soldiers had also been trained in the use of multiple tele-operated ground robots that are currently in use in Afghanistan including QinetiQ Talons, iRobot PackBots, and others. During the assessment, users could make use of the mine roller developed with Humanistic Robotics Inc. or the mine flail which was developed by Mesa Technologies (see Figure 1, image on right). One ACER was set up for tele-operation alternately with the roller and flail while the other was configured to do lead and follow behaviors using three lasers mounted around the robot. The following largely qualitative results are based on the soldier interviews.

Results

Soldiers used both lead and follow autonomous behaviors but used the follow behavior much more than the autonomous lead behavior. When the roller or flail was attached with the robot in front, tele-operation was generally the preferred option for command and control. However, the robot which carried critical

gear behind the robot was generally used in the autonomous follow mode. Soldiers accepted the use of the autonomous follow capability and every soldier said that they understood and liked the use of the X-box controller. Soldiers preferred to walk in the tracks left by the lead robot and viewed that as safest option since the tracks set down sufficient weight to detonate most pressure-activated IEDs. Soldiers wanted to carry different equipment (e.g., food, ammo, clothes, fuel, C4 explosive, etc.) on different robots depending on priorities. The key idea was to keep critical equipment away from robots in front. Also, soldiers like the idea that robot can be used to provide cover in a gun fight.

When queried, soldiers believed lead and follow to be of equal value. Different soldiers used the system in very different ways. Some soldiers believed that the ACER with the flail should be used in front 100% of the time whereas others used the lead configuration only about half of the time. In general the soldiers reported that if they only had one robot in the patrol, they would use lead (robot preceding troops) about 60% of the time and follow for the other 40%. One major finding of the assessment very relevant to command and control was that soldiers specifically stated they did not want to drive based on GPS or based on maps. Rather they preferred a proximal interaction approach where tasking occurred based either on their own motion or based on line of sight controls from the X-box controllers.

Soldiers were asked about the optimal means to drive the robot when it was in front. Soldiers said they do not want full autonomy and want to choose the robot's path. Soldiers were asked to select a preference between the following modes: 1) Drive robot around obstacles; 2) Drive straight while waiting for directional cues and stop when an obstacle is encountered. All soldiers indicated that they would want both modes with the ability to switch between them. In regard to semi-autonomous driving, soldiers generally concurred that assisted tele-operation was a good idea. However, the soldiers wanted reactive driving assistance and not the long range autonomy they had been asked to use in conjunction with other systems. They also emphasized the need for a simple controller. Also, although the X-Box controller was generally well liked, there were comments received that the best case would be to use a one hand controller together with a small graphical interface that can be used when there was a possible hazard detected. One of the reasons given was that in Afghanistan, insurgents often target those they see handling the controller. They tend to shoot at whoever they see holding a belly box or large controller because of the value of the asset and also because the workload of the user prevents them from gaining situation awareness and shooting back. If soldiers could use a small single hand controller most of the time and only get a graphical controller out of their cargo pocket when needed to analyze a hazard, it would help to alleviate the problem of insurgents targeting the person with the controller.

Another finding is that soldiers liked the wagon-training capability where they could have one robot follow another. Every soldier questioned said they would prefer three robots on each patrol with the ability to wagon train them. Three formations were suggested. For the first the three vehicles can move together with each subsequent vehicle overlapping laterally such that the next vehicle follows some meters back with its right tracks in the path of the preceding robot's left tracks. The stagger would be sufficient to do large roads. The second mode was a 3 robot convoy without lateral stagger where they would want a flail on the first robot, roller on the second robot and then pack mule on the 3rd (if available) to carry critical gear which they would not want to be destroyed. The third wagon train mode would be a 3 robot convoy where the first robot used ground penetrating radar (GPR) or some other means of explosives detection, the second robot used either a flail or roller and the third robot carried equipment. Soldiers said if they could only take one implement and one robot they would take a flail.

A number of high-level requirements for a dismounted squad support robot were derived based on the assessment. These include the ability for the support robot to provide a power hookup and to charge military batteries. Providing power while on a long mission is a critical priority and batteries are relatively heavy. Another derived requirement is to be able to tote a smaller robot on the larger ACER robot. The smaller robot can be used to enter bunkers, tunnels, caves and buildings as well as go the "last mile" on very narrow goat trails. Finally, soldiers wanted to use the smaller robot for interrogation/neutralization of roadside hazards. Soldiers reported that the overall patrol needs to carry a total of 1200lbs of equipment and that endurance is key as some missions last multiple days. Another interesting finding was that soldiers prefer to walk in the tracks left by the robot and view that as the safest option.

A variety of findings were communicated relative to the neutralization capability. Soldiers liked the flail best of the neutralization capabilities because of its ability to churn up both command detonated (e.g., detonation signal transmitted through buried wires) and pressure activated hazards reliably. Soldiers also liked the flail because of the easy replace-ability of chains and spikes which spin to dig into the ground. Soldiers said that the other flails and rollers they had used in the past were too big, too heavy and too wide but that the ACER flail was ideal as it was slightly wider than the vehicle and was wide enough to allow two soldiers to walk abreast.

Assessment Two

The idea of the "Lighten the Load" mission is that autonomous robots can shoulder the burden that soldiers currently have to carry. Soldiers today carry over 100lbs of equipment which slows them down and can sometimes cause permanent injury. Another benefit of the robot is to provide power using a generator and inverter which can charge batteries and power a variety of other equipment. Finally, the vehicle can also be driven in a tele-operated fashion to perform a variety of reconnaissance tasks to scout ahead of the squad when needed. The enabling technology is the follow capability which uses laser tracking to autonomously follow the soldiers through a variety of terrain. Another benefit of the laser based behavior is that it provides smooth, accurate tracking and allows the vehicle to get around obstacles and untagged entities (i.e. people and manned vehicles) safely. Two key elements of the assessment were the workload imposed on the soldier operating the system and ability of the system to sustain extended operational scenarios.

Test Execution

The system was loaded with approximately 200 pounds (sandbags, water, and assorted personal items), powered on using generator power at 0745, and placed in "follow-me" mode. Test attendees then took turns leading the robot over varied terrain in the 47-acre Mobile Military Operations on Urban Terrain (MOUT) compound. The control device was a common Microsoft X-Box controller. Terrain that was covered included an asphalt road, gravel road, and off-road terrain (including mud, grassy fields, and leaf-covered forest soil). The terrain included hills up to 12% incline and -12% declines. Leaders took several short-duration breaks (approx. 5 minutes) and several longer breaks (approx. 15 minutes) to simulate rest breaks during patrols. After 3 hours and 32 minutes of near-continual movement, the fuel tank was approximately half-full and the batteries retained a full charge. The generator was switched off, and the system was run on battery power only. The system was run on battery power for 3 hours and 23 minutes before it was necessary to pause the test due to lighting. At this point, the batteries retained a 30% charge. The generator was turned on to charge batteries, and all system components were left on during the 1 hour

and 50 minute safety break. At the conclusion of the break, the batteries retained a 50% charge. The system was then operated on generator power in light-to-moderate rain for an additional 37 minutes until darkness and weather conditions necessitated ending the test.

Over the course of 9 hours and 22 minutes, the system covered 16 miles, at an average rate of 1.7 miles per hour. Excluding safety breaks, the system traveled at an average rate of 2.1 miles per hour. The system was able to follow autonomously 99% of the time and required no interventions from the user (holding an X-Box controller) except in off-trail, wooded conditions where it occasionally saw weeds as obstacles. After 16 miles, the test ended with approximately 50% of battery life and 33% of the fuel remaining in the generator. Although the average overall speed was between just over 2mph, the robot did do one half mile segment at an average speed of 4.4mph. Also, there was one 1.5 mile segment that was logged at an average of 3.4mph. At the end of the test, the gas tank was approximately 1/3 full, and the batteries retained a 50% charge. The Army program management representatives who ran the test stated that the test results indicated that the robot could keep up with a patrol throughout the course of a mission which generally lasts 10-12 miles.

Figure 4, which follows, is an overhead view that shows the path taken over the first 5.4 miles while traversing a variety of trails at Ft. Leonard Wood:

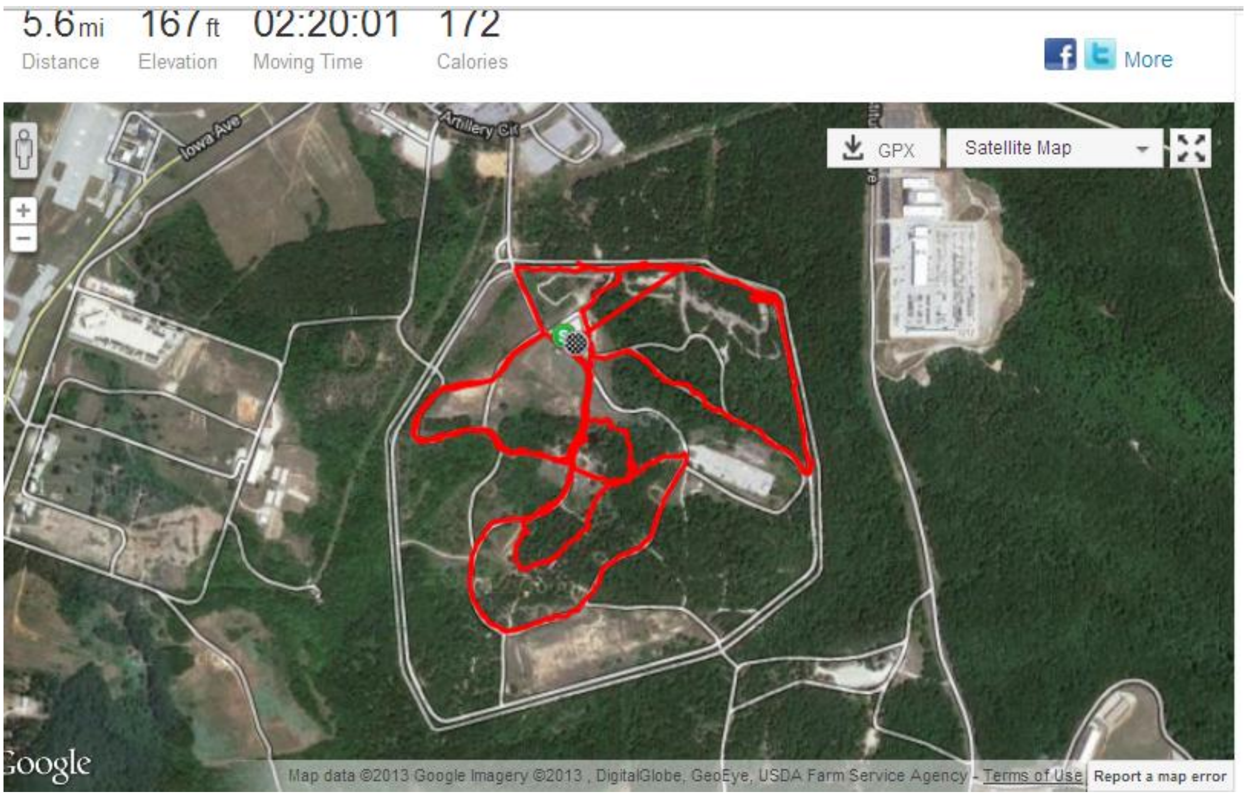

Figure 4. GPS map of area explored during patrol

Results

Soldiers indicated that they would use the system in theater and that it was both easy to understand and natural to use. They could definitely benefit from having it carry packs, but they also thought of other

uses. Here are some of the observations. During the mission, soldiers indicated that it is quite common to stop frequently and to sometimes investigate a short distance off to the side. The Segway was able to respond appropriately in these instances, following the human into the woods and often waiting behind the human matching their speed which often varied. Overall, the speed during the operational time was 2.4 mph during the test which correlates nicely with the fact that doctrine indicates an average speed of between 2-3mph during a dismounted patrol.

Assessment Three

5D worked as a subcontractor to Exponent, Inc. for the Wingman project funded by the US Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) from April 2012-April 2013. The intent of the project was to ease the burden on the solider while maintaining a low workload. The project included the development and testing of follow-me and lead-me behaviors for the command and control of an UGV.

Test execution

To assess the workload of the system a UGV Test course was designed and built by Exponent at their facilities in Phoenix, AZ. The test course included a variety of sections including: an open road, some jersey barriers, a mock Afghan village, some lightly wooded areas and a hill to ascend and descend. Sixteen runs were performed 2 for each segment of the environment. Figure 5 shows the environment where the tests were performed.

Figure 5. Exponent facilities in Phoenix, AZ where testing and performance characterization were performed.

The operator interacted with the robot using a Wii-Nunchuk that was connected to an Exponent wearable Operator Control Station that had a 1.3 Ghz Microhard radio to communicate with the robot. The operator navigated the robot through each section of the environment one or two times in both follow-me and lead-me modes.

Metrics regarding the time to complete a run, the section of the course, the total number of interventions and the total time of interventions were captured. The *intervention %* was recorded as a percentage of time the user spent intervening with the robot. An intervention is defined as a situation where the semi-autonomous capabilities of the system were unable to follow the operator and the operator had to tele-operate the robot to continue.

Results

For the follow-me tests, in 12 of the 14 test cases, the operator had no intervention with the robots. In the other two cases, the operator had only 1 intervention. In the first instance the intervention took 29 seconds out of 763 seconds (3.8% of total time). In the second instance, the operator took 52 seconds out of 206

(25.2% of total time.) Overall, the operator drove for 3462 seconds (57.7 minutes) and interacted with the system for 81 seconds (1.35 seconds) for an overall workload of 2.3%. Table 1 shows the summary of the follow-me trial runs.

Test Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	**Total**
Total Time	763	750	145	206	66	73	125	141	229	233	108	106	256	261	**3462**
Section of course	0	0	1	1	3	3	4	4	5	5	6	6	8	8	---
Intervention	1	0	0	1	0	0	0	0	0	0	0	0	0	0	**2**
Intervention time	29	0	0	52	0	0	0	0	0	0	0	0	0	0	**81**
Intervention %	3.8%	0.0%	0.0%	25.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**2.3%**

Table 1: Follow-me results showing % of time intervening with UGV

For the lead-me tests, in 10 of the 13 test cases, the operator had no intervention with the robots. In the other three cases, the operator had 1, 1, and 3 interactions respectively. In the first instance, the interaction took 15 out of 822 seconds or 1.8% of the total time. In the second instance, the interaction took 2 seconds out of 104 seconds, or 1.9% of the total time. In the third instance, the interactions took 165 seconds out of 225 seconds or 73.3% of the total time. Overall, the operator drove in lead-me mode for 2903 seconds (48.4 minutes) and interacted with the system for 182 seconds (3.03 minutes) for an overall workload of 6.3%. Table 2 shows the summary of the lead-me trial runs.

Test Run	1	2	3	4	5	6	7	8	9	10	11	12	13	
Total Time														
Section of course	0	1	1	3	3	4	4	5	5	6	6	8	8	
Intervention	1	0	0	0	1	3	0	0	0	0	0	0	0	**5**
Intervention time	15	0	0	0	2	165	0	0	0	0	0	0	0	**182**
Intervention %	1.8%	0.0%	0.0%	0.0%	1.9%	73.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**6.3%**

Table 2: Lead-me results showing % of time intervening with UGV

Conclusion

Through three real-world user assessments, new requirements have been derived that shed light on the need for proximal command and control especially for dismounted patrols. These requirements include lowering the workload to below 5%, maintaining an operational tempo of 5mph and ensuring that one or more robots can autonomously follow the squad for up to 15 miles on a narrow trail. The users also require a small visual display that shows them the relative position of each of the squad members and the robots. Most importantly, the assessments indicate that there is a potential benefit to moving away from the underlying tasking scheme of a map-based, GPS driven approach that requires continuous communication and accurate GPS to that of a “trained dog” which enables reactive, nearest-neighbor interaction which is more useful, robust and intuitive.

To further advance the potential for proximal interaction, 5D has recently developed an UWB tracking capability that allows the robots to follow the squad in fog, rain, dust and through thick vegetation. It also allows the system to see through thin obstacles and around corners. Another advantage is that with the UWB system on board the robots, the patrol members can track the position not only of the robot but of each member of their squad in real time. The Android application screen shot shown in Figure 6, shows the current system as seen from the UWB capability on the ACER robot. Notice that there are both people tags and vehicle tags and that the abstracted laser data from the robot is also presented (e.g., colored bars) to provide situation awareness regarding non-tagged entities and laser detected obstacles in the nearby environment. As entities get closer to the robot (or the robot gets close to them), their color changes to indicate proximity to the user (e.g., nearer objects red, then yellow, and green). This new positioning technology configuration is going out to be tested in Afghanistan this year to provide a squad support capability to dismounted soldiers.

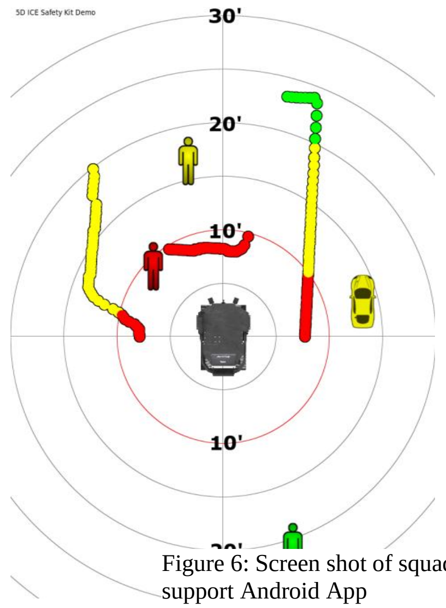

Figure 6: Screen shot of squad support Android App

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